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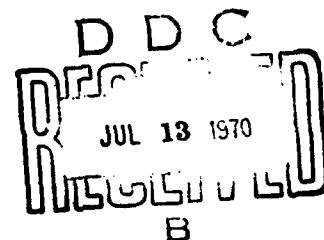
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METHOD OF DETERMINING HAIL COVERAGE WITH
AN AIRBORNE INFRARED THERMOMETER

by

Albert R. Tebo

May 1970



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AN AIRBORNE INFRARED THERMOMETER

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U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY

Abstract

The fraction of a given area of ground that is covered by hail can be determined by using an airborne infrared thermometer. If the ambient ground temperature and the hail-covered ground temperature are measured with the same thermometer, and the surface of the hail is assumed to be at a temperature of 0°C, then a simplified equation enables the determination of fractional coverage with a maximum error of 0.03 in all expected temperature regimes. Variations in the wavelength passband of the radiation thermometer and in the emissances (emissivities) of the surfaces are taken into account in the equation.

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METHOD OF DETERMINING HAIL COVERAGE WITH AN AIRBORNE INFRARED THERMOMETER

INTRODUCTION

In a study of hail storms it is important to know the intensity and extent of the hail fall. In common practice, gauges are used to measure hail intensity and visual or photographic observation are used to determine the area covered by the hail. The use of gauges necessitates a fortuitous selection of sites where hail is expected to fall. This has its drawbacks, since only a limited area can be covered with the gauges.

A technique for determining the fraction of ground covered by hail within a given hail fall, using an airborne infrared thermometer, was suggested by Dr. Helmut K. Weickmann.¹ The technique was used by him in the 1968 Joint Hail Research Project in northeastern Colorado and involved the use of a staring radiometer to measure the temperature of the hail-covered ground and the temperature of the uncovered surrounding ground. A simple radiation formula enabled the calculation of the desired quantity. The same radiometer was also used in a crude way to determine the extent of hail fall on the ground by flying back and forth in a zigzag pattern across the hail swath. Thus, some of the difficulties of ground-based techniques were largely avoided.

This paper presents the complete radiation formula for determining the fractional coverage of hail and analyzes the extent of errors involved in reducing that equation to a simplified approximation. For all practical purposes, it is found that a very simple expression can be used.

DISCUSSION

Fractional Hail Coverage

If hail at a uniform temperature spottedly covers the ground (also at a uniform temperature), the fraction of the ground covered by the hail can be determined by the resultant temperature indicated by an infrared radiation thermometer mounted in an aircraft. The thermometer under consideration, a form of staring radiometer, is mounted in a fixed position in the aircraft so that it looks vertically downward. With a nominal two-degree field of view it can "see" a circular area on the ground of 10.5-foot diameter from a height of 300 feet, 17.5 foot diameter from 500 feet, and 35.0-foot diameter from 1000 feet. The wavelength passband of the radiometer is nominally 8-14 micrometers, but the actual cut-off wavelengths

1. Weickmann, Helmut K., "Essa-1968-Colorado Hail Research",
ESSA Research Laboratories Technical Report, unnumbered, undated.

may be nearer 9 and 13 micrometers for any given radiometer. Hence both sets of limits will be considered in the analysis. It should be realized that variation in the field of view would not affect the validity of the analysis, but would only affect the spatial resolution of the radiometer.

We make the assumptions that: (1) the hail is at a temperature of 0°C; (2) the hail emits as a gray body within the wavelength passband of the radiometer with an emissance of 0.990,^{2,3} (3) that the hail and the ground are Lambertian radiators, that is, their radiance is constant in all directions; and (4) the target area fills the field of view of the radiometer. We further assume that any reflected radiation originating from the sun and sky in the passband of the radiometer is negligible. This assumption is true for a cloudless sky. Reflected radiation originating from clouds tends to compensate for loss of energy due to non-unity emissance of the surface of the terrain. By assuming a cloudless sky, we are considering the worst condition possible.

If F is the fraction of target area A covered by hail, and $(1-F)$ is the fraction of A which is bare or rain-covered, then the total irradiance due to radiation from hail and ground detected by the radiometer in its passband, and neglecting radiation reflected from the ground, is

$$H = \theta f_H F A \epsilon_H N_H + \theta \epsilon_G F_G (1-F) A N_G ,$$

where

N_H = radiance from the hail,

N_G = radiance from the bare or rain-covered ground,

f_H = fraction of radiation from the hail at temperature T_H that lies in the passband,

f_G = fraction of radiation from the bare or rain-covered ground at temperature T_G that lies in the passband,

ϵ_H = emissance of hail in the passband,

ϵ_G = emissance of bare or rain-covered ground in the passband,

θ = field of view of the radiometer.

-
2. Griggs, M., "Emissivities of Natural Surfaces in the 8-14 Micron Spectral Region", J. Geophys. Res., 73, 7545-7551, 1968.
 3. Buettner, K.J.K., and C.D. Kern, "The Determination of Infrared Emissivities of Terrestrial Surfaces", J. Geophys. Res., 70, 1329-1337 1965.

The radiometer sees the target area A as though it were a blackbody emitting with a radiance, N_E . A fraction, f_E , of this radiance is in the passband of the radiometer, giving an irradiance at the radiometer of $\theta f_E A N_E$. We then have the equality:

$$\theta f_E A N_E = \theta f_H F A \epsilon_H N_H + \theta \epsilon_G f_G (1-F) A N_G. \quad (1)$$

For Lambertian radiators, the radiant emittance, W , is equal to πN . Thus, using the Stefan-Boltzmann relation to convert to temperatures, $W = \sigma T^4$, and after eliminating θ and A , we have

$$\frac{f_E \sigma T_E^4}{\pi} = \frac{f_H F \epsilon_H \sigma T_H^4}{\pi} + \frac{\epsilon_G f_G (1-F) \sigma T_G^4}{\pi}, \quad (2)$$

where T_E is the temperature of the target area (hail-covered), as measured with the radiometer.

If we use the same radiation thermometer or one with the same filter characteristics to measure the temperature of the bare or rain-covered ground, we can use the radiation temperature of the ground, T_e , instead of the true temperature, T_G , modified by the emissance, ϵ_G . Then we obtain, after eliminating σ and π ,

$$f_E T_E^4 = f_H F \epsilon_H T_H^4 + f_G (1-F) T_e^4. \quad (3)$$

Solving for F , we get

$$F = \frac{f_G T_e^4 - f_E T_E^4}{f_G T_e^4 - f_H \epsilon_H T_H^4} \quad (4)$$

The differences between F_G , F_E , and F_H are very small compared to the fourth-powered terms for temperature differences between T_e and T_H up to 25°C. We can cancel the fractions f , and obtain the relation

$$F = \frac{T_e^4 - T_E^4}{T_e^4 - \epsilon_H T_H^4} \quad (5)$$

Furthermore, the ratio of the differences between fourth-powered terms can be closely approximated by the ratio of the differences between linear terms for temperature differences up to 25°C. By dropping the exponents and by considering the emissivity of hail to be unity instead of the actual 0.990, we arrive at the following simplified approximation, which is then expressed in terms of celsius temperature:

$$F = \frac{T_e - T_E}{T_e - T_H} = \frac{T_e - T_E}{T_e} \quad (6)$$

In application, the ambient surface temperature, which is representative of the area without hail but with the same cloud cover as the hail-covered area, is assumed to be that temperature recorded just before the sharp drop due to the presence of hail. This drop in temperature is distinctive on a chart record and can be distinguished from other drops due to terrain features such as bodies of water. In this respect, a narrow field of view for the radiometer is preferable, such as two degrees, because a wide field of view will cause a degradation of the sharpness of the record of the temperature drop due to hail.

It is assumed that the ambient surface as defined above, has the same characteristics and cloud cover as the hail-covered surface; in other words, it has the same degree of wetness (due to rain) and shading, and the same emissivity. It is also assumed that there is no hail on the surface.

Table 1 shows the errors incurred in using the simplified expression, Eq. (6), instead of the exact expression, Eq. (4). Values of F_G , f_E , and f_H , are calculated by means of a radiation slide rule involving the values of T_e and T_E , which are measured with the radiometer, and considering the temperature of hail, T_H , to be 273.15°K. The values of those temperatures are chosen to include all the representative environmental conditions that might occur during a hail storm in the United States. It is true that an arid area might be considerably warmer than 30°C before a hail storm. Realistically, the area would be subjected to a period of shading (probably by an overcast sky along with liquid precipitation) preceding the hail fall. Thus, when the radiometric temperatures are measured just after the hail has fallen, the ambient surface (which is void of hail) will be somewhat cooler, and is likely to be no warmer than 25°C.

Since the wavelength passband of the radiometer is not precisely the nominal 8-14 micrometers, the calculations are made with the exact formula using two sets of limits, 8-14 and 9-13 micrometers, in order to include variations in radiometers of this type. The data in Table 1 show that the

simplified formula deviates greatly from the exact formula at ambient surface temperatures below 10°C. However, for the large majority of cases, it is likely that the ambient surface temperature during a hail season will not fall much below 10°C. Hence the simplified formula can be considered valid under all conditions in the United States.

CONCLUSIONS

A simplified formula has been derived that makes it possible to calculate the fraction of ground covered by hail. This is done by using the temperatures of the ambient ground (not touched by hail) and the hail-covered ground, as measured by an airborne infrared thermometer, assuming the hail itself to be at a temperature of 0°C. The greatest error incurred in using this formula is only 0.03, or 3%. Hence, for all practical purposes the simplified equation can be used, making it possible to calculate hail coverage while in flight.

This technique is valid for any infrared thermometer, and the simplified formula is valid for an instrument whose wavelength passband falls anywhere within the "atmospheric window" of 8-14 micrometers. The formula is valid for terrain of any emissance and for hail whose emissance is less than unity. The formula is valid for any surface temperatures found in the United States.

TABLE 1

Errors of Approximate Equation For Fractional Hail Coverage,
8-14 and 9-13 Micrometer Passband Radiometers

Exact:

$$F = \frac{f_G T_e^4 - f_e T_E^4}{f_G T_e^4 - \epsilon_H f_H T_H^4}$$

Approximate:

$$F = \frac{T_e - T_E}{T_e}$$

		F			Error	
T _e °C	T _E °C	Approx.	Exact		8-14 Passband	9-13 Passband
			8-14 Passband	9-13 Passband		
5	0.5	0.90	0.83	0.81	+0.07	+0.09
	1.0	0.80	0.75	0.72	+0.05	+0.08
	1.5	0.70	0.66	0.64	+0.04	+0.06
	2.0	0.60	0.57	0.56	+0.03	+0.04
	2.5	0.50	0.48	0.47	+0.02	+0.03
	3.0	0.40	0.38	0.38	+0.02	+0.02
	3.5	0.30	0.29	0.29	+0.01	+0.01
	4.0	0.20	0.20	0.20	0	0
	4.5	0.10	0.10	0.10	0	0
10	1.0	0.90	0.87	0.86	+0.03	+0.04
	2.0	0.80	0.78	0.77	+0.02	+0.03
	3.0	0.70	0.69	0.68	+0.01	+0.02
	4.0	0.60	0.59	0.58	+0.01	+0.02
	5.0	0.50	0.49	0.48	+0.01	+0.02
	6.0	0.40	0.40	0.39	0	+0.01
	7.0	0.30	0.30	0.29	0	+0.01
	8.0	0.20	0.20	0.20	0	0
	9.0	0.10	0.10	0.10	0	0
15	1.5	0.90	0.88	0.88	+0.02	+0.02
	3.0	0.80	0.79	0.79	+0.01	+0.01
	4.5	0.70	0.70	0.69	0	+0.01
	6.0	0.60	0.61	0.60	-0.01	0
	7.5	0.50	0.51	0.50	-0.01	0
	9.0	0.40	0.41	0.41	-0.01	-0.01
	10.5	0.30	0.31	0.30	-0.01	0
	12.0	0.20	0.21	0.20	-0.01	0
	13.5	0.10	0.11	0.10	-0.01	0

TABLE 1 (Continued)

T _e °C	T _E °C	F			Error	
		Approx.	Exact		8-14 Passband	9-13 Passband
			8-14 Passband	9-13 Passband		
20	2.0	0.90	0.89	0.89	+0.01	+0.01
	4	0.80	0.80	0.80	0	0
	6	0.70	0.71	0.70	-0.01	0
	8	0.60	0.61	0.61	-0.01	-0.01
	10	0.50	0.51	0.51	-0.01	-0.01
	12	0.40	0.42	0.42	-0.02	-0.02
	14	0.30	0.32	0.32	-0.02	-0.02
	16	0.20	0.21	0.22	-0.01	-0.02
	18	0.10	0.11	0.11	-0.01	-0.01
25	2.5	0.90	0.90	0.90	0	0
	5.0	0.80	0.81	0.80	-0.01	0
	7.5	0.70	0.72	0.71	-0.02	-0.01
	10.0	0.60	0.62	0.62	-0.02	-0.02
	12.5	0.50	0.52	0.53	-0.02	-0.03
	15.0	0.40	0.42	0.43	-0.02	-0.03
	17.5	0.30	0.32	0.33	-0.02	-0.03
	20.0	0.20	0.21	0.22	-0.01	-0.02
	22.5	0.10	0.11	0.11	-0.01	-0.01
30	3.0	0.90	0.90	0.90	0	0
	6.0	0.80	0.82	0.81	-0.02	-0.01
	9.0	0.70	0.72	0.72	-0.02	-0.02
	12.0	0.60	0.63	0.63	-0.03	-0.03
	15.0	0.50	0.53	0.53	-0.03	-0.03
	18.0	0.40	0.43	0.43	-0.03	-0.03
	21.0	0.30	0.33	0.33	-0.03	-0.03
	24.0	0.20	0.22	0.22	-0.02	-0.02
	27.0	0.10	0.11	0.11	-0.01	-0.01

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